Research Article

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Route optimization for city cleaning vehicle

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Abstract: The basic problem concerning the waste management system is work organization, which should be effective with maximum profit and minimum financial outlays. This means that the key factor for the efficient functioning of this system are all types of costs. When collecting waste, the main operational cost factors are the driver's working time and the service time of the waste collection vehicle, as well as the route that the vehicle has to cover. The article presents route optimization solution for a vehicle collecting urban waste (both mixed and segregated) is a simple method of determining the order of driving through individual city streets. The prepared solution is universal and is not limited only to the surveyed housing estate. It presents a pattern that can be applied to other routes in a similar way. Shortening the distance and thus the working time is a result of minimizing empty runs and moving several times over the same section. Developing an optimal route for so many values requires very complicated calculations and would not reflect the real possibilities of waste collection by employees and MZGK Company. The presented solution can be used as an instruction to take the first steps to optimize the operation of the vehicle and as an initial point for further modifications of the operating system.

Keywords: waste management, route optimization, transport networks, transportation vehicle, cost reduction

1 Introduction

The basic problem concerning the waste management system is work organization, which should be effective

with maximum profit and minimum financial outlays. This means that the key factor for the efficient functioning of this system are all types of costs. When collecting waste, the main operational cost factors are the driver's working time and the service time of the waste collection vehicle, as well as the route that the vehicle has to cover [1]. The major cost factor for waste collection is the working time and the route that the city's cleaning vehicle has to take [2].

The main components of total costs also include vehicle purchase costs and necessary operating costs [3]. The largest of them are related to fuel consumption [4]. They are the main components of the Total Costs of Ownership (TCO) [5]. The cost of purchasing a vehicle usually depends on its build quality and the engine unit. In the 21st century, hybrid [6, 7] and electric drives [8, 9] are usually used. This is evidently due to the advantages they have in relation to traditional drives based on gasoline and diesel-fuelled engines [10, 11]. The use of alternative fuels plays a significant role in optimizing the costs of the vehicle fleet [12, 13]. The most popular of them are gaseous fuels such as LPG [14, 15], CNG and hydrogen [16]. Ethanol and biofuels for diesel engines are also very popular [17, 18].

Thus, a fleet of vehicles for the transport of municipal waste can be purchased in a selected standard or converted to an alternative fuel depending on the price of a given fuel on a given market [19]. The price of fuel accounts for a large share of TCO and often determines the competitiveness of a given enterprise. Companies using an obsolete fleet must take into account higher costs of operating the company.

Presently, ecology is one of the main criteria for selecting vehicles for a municipal waste disposal company. Only low-emission vehicles can enter many centres of European and global metropolises. Owners of vehicles that do not meet the latest Euro 5 and Euro 6 emission standards often have to deal with the additional costs of travelling on selected routes [20]. Alternatively, they are legally forced to replace their vehicle fleet with low-emission vehicles.

Electric vehicles have accounted for an increasing percentage of newly sold vehicles in Europe and around the world since 2010 [13]. They have many advantages over internal combustion vehicles. The most important of them is the lack of exhaust emissions at the place of operation of the vehicle. This is of great importance, especially in the crowded centres of large European cities. A significant ad-

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vantage of an electric utility vehicle is the lack of noise [21]. Garbage collection usually takes place in the early morning. Quiet electric drives do not disturb the residents. Another advantage of electric drives is the favourable torque parameters of the electric motor. What is more, there are usually no clutch or gearbox in the vehicles, which positively translates into the comfort of the driver. Electric vehicles are unfortunately much more expensive than their combustion engine counterparts. However, the operating costs of electric vehicles are much lower. Especially when the energy for charging electric vehicle batteries comes from renewable energy sources [13].

Another power unit used in city vehicles is the hybrid system. It usually consists of an internal combustion engine and an electric motor [23]. The internal combustion engine is usually used for driving at higher speeds and with greater loads. The electric motor is responsible for driving at low speeds. It is also able to support the combustion engine during starting and acceleration. Dynamic phases in the operation of an internal combustion engine are usually responsible for high emissions of pollutants in the form of nitrogen oxides in gasoline engines and particulate matter in diesel engines. A very important advantage of hybrid vehicles is the recovery of the braking energy by means of the electric motor. As a result, the range of the hybrid vehicle can be increased by more than 10%.

Hydrogen vehicles have also been developing rapidly in recent years [16]. These are vehicles powered by electric motors. They are supplied with current from the hydrogen stored on board and compressed usually to 350 or 700 bar. Hydrogen fuel cells are responsible for converting the chemical energy of hydrogen into electricity. The advantage of hydrogen vehicles over electric vehicles with lithium-ion batteries is a very short hydrogen refuelling time and a much greater range.

Another factor affecting the operating costs of a municipal cleaning company is the choice of an optimal route [24, 25]. The choice of the route and the resulting travel costs depend on the urban development pattern [26, 27]. Choosing a vehicle with low consumption of inexpensive fuel and an optimal route for the transport task of collecting municipal waste may result in the lowest possible operating costs of the vehicle fleet [28]. When optimizing the route, algorithms for selecting the appropriate path are of great importance [29, 30]. The present paper addresses the problem of optimizing the route along which a city cleaning vehicle travels in order to collect municipal waste [31]. Its purpose is to present the conditions that affect the waste collection process on the example of the city of Dęblin in Poland. The paper also considers the possibilities of improving selected transport processes in the collection of municipal waste.

This work addresses the possibility of optimizing the route on which the city's cleaning vehicle is moving to collect urban waste. Its aim is to present the conditions which influence the waste collection process in Dęblin and the possibility of its improvement.

The conducted research, unlike the currently used methods of delivery and planning, differs in the complexity of combining many methods into one hybrid computational process. At the moment, popular algorithms used focus only on the separate optimization of one parameter, *e.g.* transport time, or the amount of raw material delivered, *etc.* tasks in the working time of drivers. The presented method combines all aspects of collecting waste in terms of the selection of vehicles, their working time, optimal routes and including these tasks in the drivers' working time.

The method is based on multi-criteria optimization for the collection and disposal of municipal waste by a specified number of means of transport. Currently, individual transporting units have their own work plan. This results in many delays, lack of adequate capacity or lack of synchronization of designated transport tasks with the given plan. Another hindering factor in the performance of the intended task is the transport of waste to the collection point. As a result, there are limits to control over the vehicles that have completed their task and are ready for further operation and the vehicles during the transport task. Verified were the approximate times of shortening the operation of collecting municipal waste using the conventional method and with the use of the described algorithm. It was found that depending on the route, its length and the weight of the transported waste, it is possible to gain a dozen or so percent advantage during the performance of a given task. It is a modified and improved method of collecting municipal waste. The algorithm has control over all transport tasks of vehicles and is able to optimally distribute tasks. This eliminates longer journeys, transport downtime or overlapping routes involving the same location. This results in greater efficiency of the means of transport used, reduction of the time needed to perform a given operation and, consequently, increased collection of municipal waste along with its delivery to the collection point.

2 The problem of route mapping in transport networks

Considering the subject of optimization of transport activity, it is impossible to ignore the problem of the travelling salesman, commonly referred to as the travelling salesman problem (TSP). It is one of the combinatorial optimization

problems, aimed at determining the shortest route between certain points, thus obtaining the lowest cost [32]. The task of the travelling salesman is to visit n cities (each exactly once) and return to the starting point (city). This means that once all restrictions are taken into account, the route between A and B does not have to be the same as from B to A. The problem of salesman is related to the so called Hamiltonian cycle in the graph, which consists of a system of vertices contained in it exactly once [31]. The route of the salesman is created on the basis of n number of vertices, so that it is possible to return to the starting point using the shortest possible route. This involves setting up such a route that the lowest cost of its implementation will be achieved.

The obtained result can be assigned, in terms of complexity, to an exponential class. This means that it's necessary to find the Hamilton cycle by calculating the sum of the edge weight and indicating its smallest value. In this case, the required value is the distance between all points under consideration.

In the case of the travelling salesman problem, the length of the route is not always the main issue to be considered. The aim of the optimization can also be related to the discovery of the shortest route in terms of travel time. In such a case 'distance' is considered as the duration of the journey on individual sections. Another option may be determined by cost. In considering such an option, the price of the journey between the points shall be taken as the basic information. Finding a solution for all possible variants would be very time-consuming, therefore the following methods are mainly used in order to solve the task of the travelling salesman, such as:

- the 'nearest neighbour search' – consists in limiting the number of all combinations for the route, reducing it to several variants at each step of the algorithm;
- genetic algorithm – which is based on imitation of natural processes occurring during evolution, such as genetic inheritance;
- ant colony optimization algorithm – a way of searching solutions inspired by the behavior of Argentine ants looking for food in their colony.

2.1 Nearest neighbour search method

The method includes limiting the number of all combinations for the route, reducing it to several variants at each step of algorithm. It is a process of searching for the optimal route of the travelling salesman that is a cycle with minimal cost. It consists of the following steps:

- to determine the nearest (adjacent) vertices for the starting point, bearing in mind that the starting point has the lowest cost of the route;
- indication of the next nearest neighbouring vertices, for selected neighbours, other than the once previously designated, together with a calculation of individual costs generated for different combinations of the routes of the travelling salesman movement;
- the procedure is repeated in n steps, so that the vertices selected on the route of the travelling salesman are different from each other.

The 'nearest neighbour search' method boils down to limiting the number of all route combinations so that several algorithms are created in each step. This task can also be formulated using linear programming and the simplex method, with a target function:

$$K(x) = \sum_{i=1}^n \sum_{j=1}^n c_{ij} x_{ij} \rightarrow \min \quad (1)$$

Where: x_{ij} is a decision variable with values of one or zero, meaning the allocation of a given vertex to the optimal traveling salesman route.

With limitation:

$$\sum_{i=1}^n x_{ij} = 1, \quad (2)$$

$$\sum_{j=1}^n x_{ij} = 1, \quad (3)$$

$$x_{ij} = 1 \text{ or } 0 \quad (4)$$

2.2 Ant colony optimization algorithm

By creating an ant colony optimization algorithm, the scientists observed the social behaviour of an ant colony, in which survival depends on the degree of cooperation in achieving the goal *i.e.* looking for food or building on anthill. Ants alone are not able to achieve the adopted mission, only in a group, which is based on the interaction between all units of a given colony; their intelligence can be seen. Ants have an instinct that does not fail them even if they try to make their work more difficult by encountering an obstacle on the road. Initially, their response is characterized by chaotic movements, but after a while they manage to work out again the shortest way. This is done by means of pheromones (infochemical compounds), which they leave in the environment. The whole decision-making

process is presented in Figures 1–4. During the hike ants follow the food and set out random routes. When any of them finds food, they leave the pheromone all the way back to the anthill. This is to set a path for other individuals which is using their ability to sense there pheromones, follow the path by imitating the largest number of companions and also leave a suitable trail (Figure 1).

Figure 1: A diagram showing ants' behaviour when searching for food

If there is an obstacle, the ants must decide which road to take, whether to turn right or left. The possibility of choosing any path is the same (Figure 2)

Figure 2: The ants' behavioral pattern in case of an obstacle

Individuals who choose a shorter route strengthen the pheromone trace, which settles on it faster than on the longer route, as on the shorter route less substance will evaporate as opposed to the second choice (Figure 3).

Figure 3: Diagram of path selection by ants after an obstacle has appeared on the road

The result is that all ants choose the shortest route, as they head towards the food by the use of the scent, moreover they increase the intensity of the existing pheromone

by adding their own. The scent on the road is so high that the whole colony starts to follow it (Figure 4). Over time, the pheromones lose their intensity as a result of evaporation, which leads to the disappearance of the pathway when the food runs out.

Figure 4: The final path for the ant colony to get food

An attempt to create an optimization algorithm based on the behaviour of ant colonies has led to the development of the technique 'Ant Colony Optimization'. This algorithm is based on the principle that artificially created ants' colony work closely together to find the best solution to difficult optimization problems. The key element is cooperation, because everyone can find a solution individually, but only by taking joint actions can an optimal concept be created.

In order to create an ant colony optimization algorithm it is necessary to define components such as:

- Agencies – 'ants';
- Surroundings with specific paths of different lengths;
- 'pheromones' commanding movement of agents.

The principle of the form algorithm's operation in the context of the travelling salesman problems has been presented in a block diagram (Figure 5). It is based on a number of assumptions, established during the planning phase, and the need to make decisions *e.g.*:

- Each ant leaves a scented mark between the points of the route, in a size equal to the inverse of the route;
- The first routes to be travelled are selected at random, while the next ones are determined on the basis of the resultant probability, which is a function of the pheromone left and the distance between points;
- Individual points can only be visited once;
- The pheromone left by ants evaporates over time, which should be taken into account at the planning (creation) stage of the algorithm, using the coefficient of evaporation; this avoids the accumulation of the pheromone on the 'worse' routes and exposes the most commonly used routes.

Figure 5: Diagram of operation based on form algorithm

Only selecting the appropriate coefficients it is possible to find the best solution to the problem, which will be optimal for the assumptions made. At first, the ants move randomly, but after some time they are attracted to the 'better' paths, giving up those that do not meet their requirements.

2.3 Genetic Algorithm

The genetic algorithm was created on the basis of observations of nature and changes taking place in it. Optimal solutions are searched by imitation of natural processes related to evolution, i.e. genetic inheritance. Every living organism lives in a changing environment to which it adopts

better or worse. Those organisms that do better in the wild have a better chance of surviving.

The relationship can be depicted from the relation between the mouse and the cat hunting it. A fast, agile and clever cat is more likely to catch a mouse than a slow and clumsy one. Therefore, this first cat will survive and will be able to pass on its 'better' genes to future generations. Some cats from the 'worse sort' will also survive, thus introducing a mixture of genetic material. The natural reaction of the population is to strive for improvement (the 'better' organisms reproduce and the 'worse' organisms die out). The genetic algorithm works on the basis of relations presented in the Figure 6.

Figure 6: Genetic algorithm test area

Colorful circles (located in the middle of the test area) depict individuals with specific information. In relation to the problem of the travelling salesman, the wheels are cities, while the information is a reference to their location on the map, including the distance between them. The starting point of the route planning is the black point, while the red ones are the neighboring villages with the shortest distance from the start. According to the genetic algorithm, they are "better" than others. Therefore, in the first stage of route planning, it is these cities that are taken into account, while the others are initially rejected.

The selection of the initial population is made on the basis of the indication of the cities that need to be visited by the travelling salesman. The first route is indicated at random, eliminating from the list the cities already visited so as not to arrive twice. The assessment shall be based on a comparison of the distance between the points concerned. The best matching elements form the shortest route.

The process is completed when:

- the optimal value was found (the shortest route was found, or the value was reached);
- performing subsequent attempts does not allow to find a better solution;
- some specified time passed or the indicated number of attempts was over.

In the genetic algorithm, points are selected to create a new route.

Figure 7: A diagram showing the operation of a genetic algorithm

Two types of selection can be distinguished:

- elite – is based on a better/worst order of values, from best to worst, the number of the best ones should be determined;
- tournament – is characterized by pairing and then indicating the better solution in them.

Approaching the end of the process, two exemplary routes intersect in order to create a new (better) road. This is done by using one of the three ways of crossing appropriate for the travelling salesman problem:

- with partial mapping (PMX);
- with ordering (OX);
- cyclic (CX).

The last step in the genetic algorithm is to make a mutation. It consists of exchanging one or more elements in a given population. This is to introduce its variability. It is

possible to distinguish between several types of mutations, *i.e.*:

- inversion – refers to indicating a fragment of the route and then reversing the order of visited cities;
- insertion – consists in selecting a random city and inserting it in any other place;
- relocation – is characterized by indicating a fragment of the route and moving it to another place;
- mutual exchange – consists in selecting two cities and swapping them with each other.

The process, which is unambiguous to the end of the genetic algorithm, is stopped when the conditions are met. The method of genetic algorithm for finding the optimal solution for the travelling salesman problem does not always bring about finding the optimal route, but always leads to the best possible solution.

The subject matter of a single travelling salesman is an exceptional problem in the field of vehicle route planning, which is seen as a problem of many travelling salesmen. When planning a route for many vehicles, it should be remembered to meet criteria such as:

- visiting individual customers by only one vehicle;
- the load capacity for each vehicle indicated for operation cannot be exceeded;
- the price (or length) of the routes covered by all vehicles used must be the smallest.

Following these guidelines, two key issues arise in route planning, *i.e.*:

- dividing the set of all points to be visited into regions, where each area will be assigned to one vehicle;
- determining the order of visits of individual points within a given region.

The problem of routes planning for vehicles is a starting point on the basis of which it is possible to formulate derivative issues based on the modification of the basic task.

3 Waste management in Dęblin

Each product (*e.g.* a raw material, material or final product) which is not used in accordance with its performance characteristics becomes waste.

The currently efficient waste management within a given city or commune should be supported by modern logistic solutions, *i.e.* the so called reverse logistics which includes: waste logistics, reverse logistics, reprocessing, as well as recycling *x*. The aim of waste management logistics

is to find the best solutions in terms of organization and cost for transport, storage, reprocessing and disposal of the so-called rubbish.

Waste management in the area of a city or commune comes down primarily to the collection of mixed and segregated urban waste by specialized waste disposal companies.

In the area of Dęblin commune, 17 districts can be indicated, which designate individual settlements, *i.e.*: Irena, Jagiellońska, Lotnisko, Masów, Michalinów, Mierzwiączka, Młynki, Podchorążych, Pułaskiego, 15 pp "Wików", Rycice, Starówka, Staszica, Stawy, Wiślana, Wiślana-Żwica, Żdźary (Figure 8).

Figure 8: Administrative division of Dęblin [33]

The division into individual districts is also determined by the type of housing development, which main investors were: the army, railways, the city, housing cooperatives and individual investors. On this basis, the following housing estates and development complexes can be distinguished:

- single-family development – dominates mainly in the following estates: Jagiellońska, Masów, Młynki, Pułaskiego, Wiślana-Żwica, and Żdźary;
- multi-family development – *i.e.* blocks of flats located in the area of the Staszica, Stawy, Wiślana, Lotnisko, and Podchorążych housing estates;
- low-intensity development – single-family houses with accompanying services located in the city centre are predominant;

- mixed development – *i.e.* agricultural-horticultural and single-family, located along the main streets of the city – dominates within the Irena, Michalinów, Mierzwiączka, Rycice, and Starówka estates.

The principles of urban waste management in the area of the city of Dęblin have been developed in the document entitled "Waste Management Plan for the town of Dęblin".

Figure 9: Graphical route separation for a city cleaning vehicle [33]

According to this document, the collection and transport of waste in Dęblin commune is the responsibility of Miejski Zakład Gospodarki Komunalnej (MZGK) Sp. z o. o. and auxiliary company Tonsmeier Wschód Sp. z o. o. from Radom. Currently, waste collection is carried out from 13,711 inhabitants of the city and is selective for 99% of them. The total amount of mixed and selective waste in 2019 was 4 933 tones. Waste collection is carried out on the basis of a specific schedule, which divides the city into three groups in the case of mixed waste collection and two groups in the case of segregated waste. The main problem of urban waste management in this city is the vast area and the lack of landfill for mixed waste.

The process that requires improvement is the collection of three different waste items, separated and mixed from more than 816 points, which are distributed throughout the city at different densities.

When planning to optimize the work process for a city cleaning vehicle, the daily time limit, *i.e.* the driver's working time, should be reduced to 8 hours. Additionally, in

Table 1: Waste collection points on individual routes

Route number	Approximate number of containers		Total
	Single-family houses	Multi-family houses	
1	-	3	3
2	78	-	78
3	89	-	89
4	138	2	140
5	76	-	76
6	69	-	69
7	13	-	13
8	48	6	54
9	75	-	75
10	7	4	11
11	-	12	12
12	9	6	15
13	5	7	12
14	47	-	47
15	32	-	32
16	39	-	39
17	51	-	51
SUM	776	40	816

the case of segregated waste, there is a limitation in the form of receiving only one type of raw material in a given course. The collection of mixed waste generates additional time losses when the car is full, because the waste collection point (the so-called waste dump) is 20 km away from Dęblin. Here the contents of the garbage truck are unloaded and returned to the route for further collection.

The collection of waste for disposal should take place only when the bins are full. The problem is not only to determine the optimal routes for vehicles collecting urban waste, but also to indicate the location for the collection containers. According to the current policy in the company, routes are planned in an intuitive way based on the many years of experience of the employees, which prevents the use of available resources and possibilities in an optimal way.

The shortcomings that occur in waste collection mainly concern the failure to meet accepted collection deadlines and the lack of predictability and transparency of the route. This leads to contradiction with the agreed waste collection schedule and errors are recorded in working system. In order to be able to repair the system it is necessary to develop a template with the locations of the individual waste bins and to determine the estimated distances between them. On this basis it would be possible to determine the perfor-

mance of the existing system and to plan a more beneficial solution.

For the purpose of the submitted work, the problem has been simplified by graphically separating the locations into shorter routes covering the area of individual settlements. The MZGK's work system consists of providing employees with a list of locations with a random order of points to be served on a daily basis. The driver's task is to serve everyone within the set working time.

4 Optimization of the urban waste collection route in Dęblin

The criteria for the optimization of work for the urban waste treatment vehicle is the option of minimizing the length of the route that the vehicle has to travel from the place of daily stopover through specific collection points to the place of cargo return, during the days of the week imposed by the schedule. The basic constraints for route planning include the capacity of the means of transport, the driver's working time and the location of the final destination. On the basis of the presented data and collected information, the route optimization model presented in Table 2 was developed.

The main restrictive conditions in the form of statements $\sum_{j \in Y} x_{ij} = 1$ and $\sum_{i \in Y} x_{ij} = 1$ guarantee that the vehicle will not miss any point that needs to be visited to collect waste. The form $s_i + t_{ij} - (1 - x_{ij}) M_{ij} < s_j$ qualifies a continuity of the route that must be consistent between the individual points, *i.e.* when a vehicle collects waste from the first point it is followed by the second point, between which the difference cannot be less than the travel time between these points. Condition $K_i \leq s_i \leq L_i$ specifies the time slot within which the point should be visited.

Thanks to such assumptions, it is possible to determine the optimal time for a given day's route. On the basis of these assumptions, the person supervising the cleaning works (in this case, urban waste collection) may verify the correctness of the route and, in case of an inappropriate variant, develop a more beneficial variant. However, this decision model can only be used for a certain number of reception points and will not apply to a very large agglomeration. Therefore, in order to use it, Dęblin was divided into individual housing estates, where the number of reception points was estimated, which is closely related to the type of development in a given housing estate.

Two different routes have been analyzed using the above decision-making model: one housing estate with single-family houses and the other with multi-family houses. The whole process of research was carried out in

Table 3: List of the route followed by MZGK employees during the collection of mixed waste

Route section no. 3	Length of the section [km]	Travel time [min]	Number of pick-up points	Stopover time at points [min]	Total time [min]
1-2	0.5	3.3	1	0.75	4.05
2-28	1.3	8.6	3	2.25	10.85
28-25	0.7	4.6	2	1.5	6.1
25-23	0.3	2	0	0	2
23-24	0.4	2.6	1	0.75	3.35
24-17	1.2	8	5	3.75	11.75
17-18	0.5	3.3	0	0	3.3
18-22	0.9	6	4	3	9
22-20	0.6	4	2	1.5	5.5
20-21	0.4	2.6	2	1.5	4.1
21-20	0.4	2.6	2	1.5	4.1
20-18	0.3	2.6	1	0.75	3.35
18-19	0.4	2.6	2	1.5	4.1
19-16	1.5	10	4	3	13
16-4	1.3	8.6	4	3	11.6
4-5	0.4	2.6	0	0	2.6
5-14	0.9	6	3	2.25	8.25
14-15	1.1	7.3	4	3	10.3
15-14	1.1	7.3	3	2.25	9.55
14-5	0.9	6	4	3	9
5-6	0.6	4	0	0	4
6-12	1.4	9.3	4	3	12.3
12-13	1.1	7.3	3	2.25	9.55
13-12	1.1	7.3	4	3	10.3
12-8	1.4	9.3	2	1.5	10.8
8-9	0.4	2.6	1	0.75	3.35
9-10	0.8	5.3	2	1.5	6.8
10-11	0.9	6	3	2.25	8.25
11-10	0.9	6	3	2.25	8.25
10-9	0.8	5.3	4	3	8.3
9-8	0.4	2.6	0	0	2.6
8-6	0.6	4	0	0	4
6-7	0.4	2.6	1	0.75	3.35
7-4	1.7	11.3	0	0	11.3
4-26	0.7	4.6	0	0	4.6
26-27	0.9	6	3	2.25	8.25
27-29	1.0	6.6	3	2.25	8.85
29-30	0.4	2.6	0	0	2.6
30-31	1.1	7.3	3	2.25	9.55
31-32	1.0	6.6	2	1.5	8.1
32-4	0.3	2.6	0	0	2.6
4-3	0.9	6	2	1.5	7.5
3-2	1.2	8	2	1.5	9.5
Total	35.1	233.8	89	66.75	300.55

Table 4: Summary of the route of mixed waste collection after optimization by means of a decision model

Route section no. 3	Length of the section [km]	Travel time [min]	Number of pick-up points	Stopover time at points [min]	Total time [min]
1-7	4.3	28.6	6	4.5	33.1
7-6	0.4	2.6	0	0	2.6
6-8	0.6	4	0	0	4
8-9	0.4	2.6	1	0.75	3.35
9-10	0.8	5.3	6	4.5	9.8
10-11	0.9	6	3	2.25	8.25
11-10	0.9	6	3	2.25	8.25
10-12	0.4	2.6	0	0	2.6
12-13	1.1	7.3	3	2.25	9.55
13-12	1.1	7.3	4	3	10.3
12-6	1.4	9.3	6	4.5	13.8
6-5	0.6	4	0	0	4
5-14	0.9	6	7	5.25	11.25
14-15	1.1	7.3	4	3	10.3
15-14	1.1	7.3	4	3	10.3
14-16	0.4	2.6	0	0	2.6
16-19	1.5	10	4	3	13
19-18	0.4	2.6	2	1.5	4.1
18-20	0.3	2.6	1	0.75	3.35
20-21	0.4	2.6	2	1.5	4.1
21-20	0.4	2.6	2	1.5	4.1
20-22	0.6	4	2	1.5	5.5
22-18	0.9	6	4	3	9
18-17	0.5	3.3	0	0	3.3
17-23	0.8	5.3	4	3	8.3
23-24	0.4	2.6	1	0.75	3.35
24-23	0.4	2.6	0	0	2.6
23-25	0.3	2.6	0	0	2.6
25-28	0.7	4.6	2	1.5	6.1
28-29	0.4	2.6	2	1.5	3.35
29-26	1.9	12.6	6	4.5	17.1
26-32	0.4	2.6	4	3	5.6
32-30	2.1	14	5	3.75	17.75
30-2	0.3	2.6	1	0.75	3.35
2-1	0.5	3.3	0	0	3.3
Total	29.6	197.9	89	66.75	263.9

Table 5: Comparison of the length of the routes and their travel time for the compiled variants

Options under consideration for the survey	Route length	Time travel with waste collection
The route followed by MZGK employees	35.1 km	300.55 min
Optimized route	29.6 km	263.9 min

Table 6: List of the route followed by MZGK employees during the collection of segregated waste

Route section no. 3	Length of the section [km]	Travel time [min]	Number of pick-up points	Stopover time at points [min]	Total time [min]
1-2	0.5	3.3	1	0.3	3.6
2-28	1.3	8.6	3	0.9	9.5
28-25	0.7	4.6	2	0.6	5.2
25-23	0.3	2	0	0	2
23-24	0.4	2.6	1	0.3	2.9
24-17	1.2	8	5	1.5	9.5
17-18	0.5	3.3	0	0	3.3
18-22	0.9	6	4	1.2	7.2
22-20	0.6	4	2	0.6	4.6
20-21	0.4	2.6	2	0.6	3.2
21-20	0.4	2.6	2	0.6	3.2
20-18	0.3	2.6	1	0.2	2.8
18-19	0.4	2.6	2	0.6	3.2
19-16	1.5	10	4	1.2	11.2
16-4	1.3	8.6	4	1.2	9.8
4-5	0.4	2.6	0	0	2.6
5-14	0.9	6	3	0.9	6.9
14-15	1.1	7.3	4	1.2	8.5
15-14	1.1	7.3	3	0.9	8.2
14-5	0.9	6	4	1.2	7.2
5-6	0.6	4	0	0	4
6-12	1.4	9.3	4	1.2	10.5
12-13	1.1	7.3	3	0.9	8.2
13-12	1.1	7.3	4	1.2	8.5
12-8	1.4	9.3	2	0.6	9.9
8-9	0.4	2.6	1	0.3	2.9
9-10	0.8	5.3	2	0.6	5.9
10-11	0.9	6	3	0.9	6.9
11-10	0.9	6	3	0.9	6.9
10-9	0.8	5.3	4	1.2	6.5
9-8	0.4	2.6	0	0	2.6
8-6	0.6	4	0	0	4
6-7	0.4	2.6	1	0.3	2.9
7-4	1.7	11.3	0	0	11.3
4-26	0.7	4.6	0	0	4.6
26-27	0.9	6	3	0.9	6.9
27-29	1.0	6.6	3	0.9	7.5
29-30	0.4	2.6	0	0	2.6
30-31	1.1	7.3	3	0.9	8.2
31-32	1.0	6.6	2	0.6	7.2
32-4	0.3	2.6	0	0	2.6
4-3	0.9	6	2	0.6	6.6
3-2	1.2	8	2	0.6	8.6
Total	35.1	233.8	89	26.6	260.4

Table 7: Statement of the route of the waste collection after optimization by means of a decision model

Route section no. 3	Length of the section [km]	Travel time [min]	Number of pick-up points	Stopover time at points [min]	Total time [min]
1-7	4.3	28.6	6	1.8	30.4
7-6	0.4	2.6	0	0	2.6
6-8	0.6	4	0	0	4
8-9	0.4	2.6	1	0.3	2.9
9-10	0.8	5.3	6	1.8	7.8
10-11	0.9	6	3	0.9	6.9
11-10	0.9	6	3	0.9	6.9
10-12	0.4	2.6	0	0	2.6
12-13	1.1	7.3	3	0.9	8.2
13-12	1.1	7.3	4	1.2	8.5
12-6	1.4	9.3	6	1.8	11.1
6-5	0.6	4	0	0	4
5-14	0.9	6	7	2.1	8.1
14-15	1.1	7.3	4	1.2	8.5
15-14	1.1	7.3	4	1.2	8.5
14-16	0.4	2.6	0	0	2.6
16-19	1.5	10	4	1.2	11.2
19-18	0.4	2.6	2	0.6	3.2
18-20	0.3	2.6	1	0.3	2.9
20-21	0.4	2.6	2	0.6	3.2
21-20	0.4	2.6	2	0.6	3.2
20-22	0.6	4	2	0.6	4.6
22-18	0.9	6	4	1.2	7.2
18-17	0.5	3.3	0	0	3.3
17-23	0.8	5.3	4	1.2	6.5
23-24	0.4	2.6	1	0.3	2.9
24-23	0.4	2.6	0	0	2.6
23-25	0.3	2.6	0	0	2.6
25-28	0.7	4.6	2	0.6	5.2
28-29	0.4	2.6	2	0.6	3.2
29-26	1.9	12.6	6	1.8	14.4
26-32	0.4	2.6	4	1.2	3.8
32-30	2.1	14	5	1.5	15.5
30-2	0.3	2.6	1	0.3	2.9
2-1	0.5	3.3	0	0	3.3
Total	29.6	197.9	89	26.6	224.5

Table 8: Comparison of the length of the routes and their travel time for the compared variants

Options under consideration for the survey	Route length	Time travel with waste collection
The route followed by MZGK employees	35.1 km	260.4 min
Optimized route	29.6 km	224.5 min

to their own intuition is presented in Table 3, taking into account the length of the section and the time needed to cover it.

The table below shows that the route followed by MZGK employees based on GPS records is 35.1 km. The journey of this section at a speed of 9 km/h without stopping for waste collection takes about 4 hours on average. Taking into account all the houses that are located on this estate and assuming that each property has only one container this time is extended by about 1 hour 7 min. The measurements show that the average time spent by the employees on the task of collecting municipal waste for this housing estate is about 5 hours.

After applying optimization mechanisms, the length of the route decreased to 29.6 km, and the expected time of driving along the designated route was about 3 hours and 17 minutes. The service time of all the containers is constant, as the quantity remains the same. The final time of waste collection from all points decreased to about 4h excluding unplanned stops (Table 4).

The difference between the route adopted by employees and the mathematically optimized option is a total of 5.5 km. The time difference is about 37 minutes of work. This is the time that can be used to get to the waste collection point or in the case of loading capacity, a quicker route on the next housing estate (Table 5).

In the second case, the measurements were made for the collection of segregated waste, assuming a speed of 9 km/h and a stopover time for emptying the container of 20 s. An additional limitation was the possibility of collecting only one type of waste during one course. Due to the schematic course, the measurements were made only during plastic waste collection. The route the crew was travelling according to their own intuition is presented in Table 6, taking into account the length of the section and the time needed to complete it.

Table 6 below shows that MZGK employees operate in a schematic manner and follow the same route as during the collection of segregated materials. The route is 35.1 km long. The journey of this section at a speed of 9 km/h without stopping takes about 4 hours on average. Taking into account all the pick-up points which are located on this housing estate and assuming that each property has only one container, the travel time is extended by about 26 minutes. The measurements show that the average time the employees spend on the task of collecting segregated waste for this housing estate is about 4.5 hours.

After applying the optimization mechanisms presented in the first variant of the study, it was possible to shorten the route to 29.6 km, while the expected time of travel was reduced to about 3 hours and 17 minutes (Table 7).

The service of all pick-up points is unchanged as the number of containers to be emptied remains the same. The final travel time for collecting segregated waste from all points has decreased to about 3 hours, excluding unplanned stops.

The time difference between the route taken by MZGK employees and the optimized variant is about 35 minutes (Table 8). This time is sufficient to speed up the process of collecting the next raw material after emptying the trailer. In the case of segregated materials, the time of delivery to the collection point is much shorter due to its location within the city.

The analysis shows that the use of even the simplest route optimization methods for an urban waste cleaning vehicle contributes to shortening the driver's working time and speeding up collection in individual regions. As a result of the research carried out, it was found that the freedom left to drivers adversely affects the implementation of the whole process and generates deviations from the actual time needed to make a given journey. Leaving the route arrangement to the driver's freedom generates very long delays for the entire waste collection schedule, resulting in overtime. Managers should analyze all the possibilities of a given route and analyze the acceptance schedule in order to work out the most advantageous solutions.

5 Conclusion

The presented route optimization solution for a vehicle collecting urban waste (both mixed and segregated) is a simple method of determining the order of driving through individual city streets. The prepared solution is universal and is not limited only to the surveyed housing estate. It presents a pattern that can be applied to other routes in a similar way. Shortening the distance and thus the working time is a result of minimizing empty runs and moving several times over the same section.

Implementation of the presented algorithm and its results clearly indicate the reduction of the time of waste collection and delivery to the collection point and the appropriate selection of available means of transport. This has resulted in a reduction of idle downtime and an increase in the efficiency of the entire waste disposal process, which would take more time and effort in the case of conventional methods.

The proposed methodology in terms of practical applications directly affects the synchronization of waste transport in terms of the load capacity of transport means. This translates into the optimal distribution of the waste load of

vehicles ready for the performance of transport tasks. This results in a lack of delays and eliminates the reporting of more vehicles for the transport task than necessary.

The proposed solution also has limitations, resulting from the vast area and number of locations to be served. The company in the area of Dęblin has the task of collecting waste from 819 points. Developing an optimal route for so many values requires very complicated calculations and would not reflect the real possibilities of waste collection by employees and MZGK Company. The prepared solution can be used as an instruction to take the first steps to optimize the operation of the vehicle and as an initial point for further modifications of the operating system.

Future works will be aimed at improving the efficiency of the system in terms of organization and scheduling of transport tasks of the means of transport used for waste collection. The disadvantages may consist in discrepancies in the reported weight and dimensions of the material intended for transport.

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